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UNIQUE ANAMORPHIC LENS DESIGN USED FOR FEMTOSECOND MICROMACHINING IN TRANSPARENT BULK MATERIALS (PREPRINT)

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Survivability and Sensor Materials Division

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14. ABSTRACT
A unique anamorphic lens design was applied to a circular 780nm femtosecond laser pulse to transform it into a narrow line spread at focus. This lens was developed to give an alternative method of micromachining bulk transparent materials. The challenge for femtosecond laser processing is to control the nonlinear affect of self-focusing, which can occur when using a fast f-number lens. Once the focused spot is dominated by self-focusing the predicted focused beam becomes a filament inside the bulk, which is an undesirable effect. The anamorphic lens resolves this self-focusing result by increasing the numerical aperture (NA) and employing an elliptical beam shape. The anamorphic lens was also designed to furnish a 2.5 um by 190 um line spread that will exceed a transparent bulk material's damage threshold in a single femtosecond laser pulse. Damage in this text refers to visual change in the index of refraction as observed under an optical microscope. Using this line spread, grating structures were micro-machined on the surface of SiC bulk transparent substrate.

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Unique Anamorphic Lens Design Used For Femtosecond Micromachining in Transparent Bulk Materials

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Abstract – A unique anamorphic lens design was applied to a circular 780nm femtosecond laser pulse to transform it into a narrow line spread at focus. This lens was developed to give an alternative method of micromachining bulk transparent materials. The challenge for femtosecond laser processing is to control the nonlinear affect of self-focusing, which can occur when using a fast f-number lens. Once the focused spot is dominated by self-focusing the predicted focused beam becomes a filament inside the bulk, which is an undesirable effect. The anamorphic lens resolves this self-focusing result by increasing the numerical aperture (NA) and employing an elliptical beam shape. The anamorphic lens was also designed to furnish a 2.5μm by 190μm line spread that will exceed a transparent bulk material's damage threshold in a single femtosecond laser pulse. Damage in this text refers to visual change in the index of refraction as observed under an optical microscope. Using this line spread, grating structures were micro-machined on the surface of SiC bulk transparent substrate. SiC was chosen for it is known for its micromachining difficulty and because it is a known crystalline structure. Grating structures were chosen for this study to give alternative methods of micromachining gratings in bulk transparent materials. Current methods of manufacturing gratings in bulk transparent materials require dopant and complex interference patterns (i.e. fiber Bragg gratings). The grating structure characterization provides evidence that the anamorphic lens produces a line spread nearly identical to the geometrical approximation.

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1. Introduction

Femtosecond (fs) lasers have become an important tool for micromachining and fabrication of photonic devices. Their unique ability of inducing permanent index changes into just about any transparent material is due to fast focusing conditions, resulting in very high intensity causing nonlinear multi-photon absorption. Former research has theorized that the ultra-fast pulse is too short to interact at the molecular level, and instead interacts at the atomic electronic level [1]. It is also theorized that the fs pulse displaces electrons permanently and/or causes lattice changes resulting in a modification to the index of refraction [2]. The modification to the index is localized to a small volume depending on the NA and energy used. These index alterations can be on the surface or in most cases subsurface in bulk material.

SiC is an attractive alternative material for a variety of semiconductor devices where silicon (Si) lacks the environmental resistance that carbon furnishes when combined to Si. These areas where SiC devices can be used include high-power high-voltage switching applications, high temperature electronics, and avionics where the reduction of payload due to many wires are needed to keep sensitive Si-based electronics away from extreme environments onboard aircraft [3].

The SiC sample tested is a semi-insulating type and its characteristics are shown in Table 1 below. The sample in Table 1 was perpendicularly oriented on the c-plane with the vertically polarized anamorphic beam.

Table 1: SiC sample characteristics for the semi-insulating type. The SiC semi-insulating values come from the vendor, Intrinsic Corp.

Sample	Conductivity	Orientation	Dopant	Concentration (cm^{-3})	Resistivity ($\Omega\cdot cm$)	Thickness (μm)	Face	N or P Type
SiC semi-insulating	Semi-insulating	c-Plane, 6H 0° on axis	Undoped	$\sim 1x10^{15}$	3x10	340	Si	---

In this paper we discuss a new method of writing gratings (or other types of structures) in bulk transparent materials using a single femtosecond laser pulse. We will investigate the grating structures visually (inspected under an optical microscope) and also by use of an atomic force microscopy (AFM). In addition, we test the grating diffraction efficiency (DE) as a function of grating spacing, d.

Our method of micromachining gratings uses an anamorphic lens to distribute the ultrafast (UF) laser pulse from a 5.5mm round Gaussian distribution to a 2.5μm by 190μm line shape. The gratings were micro-machined in semi-insulating SiC using automated xyz stages controlled by Labview in a direct write configuration. The samples were irradiated with a single laser pulse by use of a chopper wheel and a high speed shutter combination. The fs laser pulses were generated using a Clark-MXR CPA-2010 laser system, with a wavelength of 780nm, a pulse width of 150-200fs, M2 = 1.55 and a maximum energy of 1mJ/pulse. Grating structures were written into the SiC by successively machining 2.5μm by 190μm lines end-to-end to form an individual machined line (about 500μm long). This process was repeated such that each grating consisted of three columns of 2.5μm wide by 190μm long index modified lines and 25 rows of center to center grating line spacing of 20μm. The individual grating lines overlap approximately 5-10μm. These dimensions produce approximate 500μm by 500μm gratings in the transparent substrates.

This method of micromachining gratings is an alternative to interference techniques and/or circular spot direct writing using high speed translation of the sample. It provides accurate micro-machined gratings in the absence of any self-focusing from the use of a highly elliptical beam [4]. An elliptical beam has a much higher damage threshold than that of symmetrically round beams due to the lack of self-focusing in the substrate [4]. In our experiments, the numerical aperture is very large in one axis, which results in a lower damage threshold for femtosecond radiation. The idea/theory is that a large NA in combination with an elliptical beam will decrease the chances of any self-focusing occurring within the bulk of the sample. Self-focusing filamentation will spoil the micro-machined features, which will result in unpredictable/undesired micro-machined features. The gratings produced with the anamorphic lens resist any nonlinear self-focusing attributes, and results in "clean" accurate gratings that closely resemble the geometrical profile.

2. Experimental Setups

The anamorphic lens micromachining experiment was completed using a single laser source split to provide ~50μJ to the experiment. Figure 1 below illustrates the experimental setup.

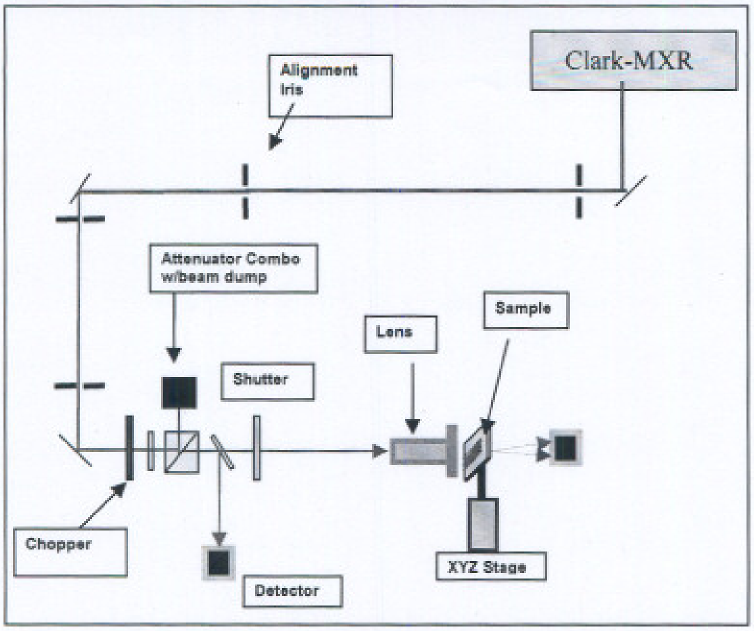

Figure 1 Setups for the anamorphic lens micromachining experiment.

Figure 1 gives the experimental setup for the anamorphic lens micromachining experiment. The Clark-MXR femtosecond laser system is split into multiple beam paths for different tests, and a 50μJ portion of that is split for the experiment. In the experimental setup there is a polarizer beam splitter and ½ wave plate combo used to attenuate the beam. The experiment uses the anamorphic lens to morph the 5.5mm circular beam into a 2.5μm x 190μm line distribution as described in the Introduction section.

The experiments use input and output photodiodes to measure the incident pulse energy verses the transmitted energy through the sample. Each photodiode is calibrated using a pyroelectric Joule meter (traceable to National Institute of Standards). Also a chopper wheel and a high speed shutter which together work automatically control the number of pulses to the sample. Finally, the sample is held on a xyz automatic stage controlled with ± 1μm accuracy. The entire illumination collection procedure is automated. Before the experiment is run, the beam input into the anamorphic lens is completely characterized with pulse width, M^2, and profile measurements. The M^2 refers is a measured quantity that is used to characterize the deviation from diffraction limited focusing (M^2 of 1 represents the diffraction limit, and real beams have $M^2 > 1$). The NA was measured in both axes, x and y.

3. Anamorphic Lens Design

The design and analysis of this anamorphic lens design was accomplished using Zemax. Figure 2 below shows a solid layout and a ray distribution through focus of the anamorphic lens.

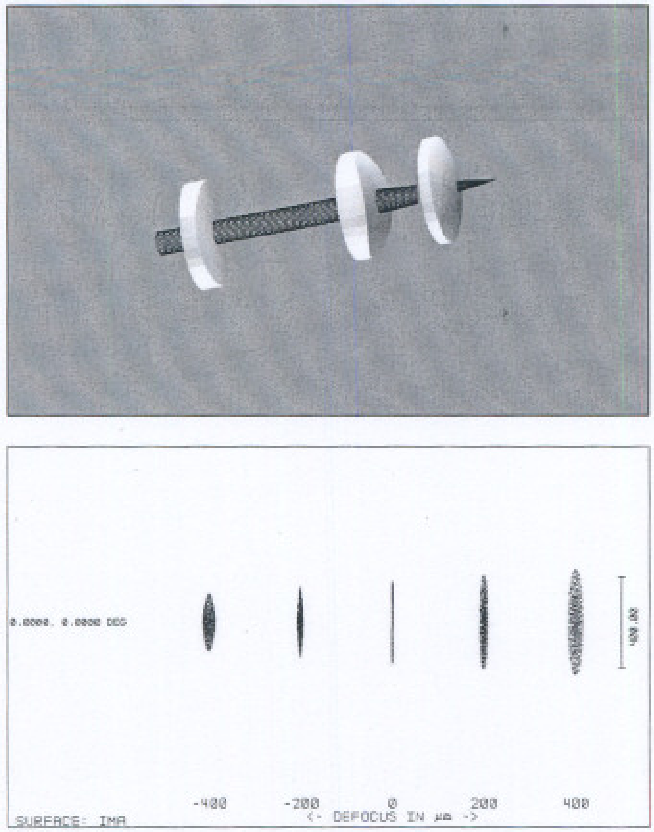

Figure 2 Zemax analytic views of the anamorphic lens used spread the focused beam elliptically. Top is a Zemax solid layout displaying each lens and their relative position in the lens tube (on the left is a 100mm focal in x, middle is a 50mm in y, and on the right is the spherical lens), and Bottom is a plot of the ray distribution through focus ± 400µm, where at defocus = 0µm is the anamorphic line shape used for laser processing.

This lens shown in Figure 2 was designed to transform the 5.5mm circular beam into a 2.5µm by 190µm line distribution as shown in Figure 2. The x-dimension uses a 100mm focal length cylindrical lens and the y-dimension uses a 50mm focal length cylindrical lens. The last lens is a spherical lens, which is used to further assist the x and y foci into a slightly tighter focus. A spherical lens was used to assist the two cylindrical lenses to provide a line spread of high enough fluence above the damage threshold (DT) of the SiC substrate, and is given in units of J/cm^2. Damage in this context refers to substrate modification observed under an optical microscope. The numerical aperture, NA, for this anamorphic lens system is 0.085 given by Zemax. A general NA equation is given below [5].

$$NA = \frac{D}{2f} = n\sin(\theta) = \sqrt{n_1^2 - n_2^2}, \quad \text{Equation 1}$$

where D is the entrance aperture diameter, f is the effective focal length (EFL) of each axis, n, is the index of refraction, and θ is the angle of the cone angle. The NA of this anamorphic lens system was found geometrically using the Zemax theoretical model and confirmed experimentally by performing a M^2 used to extract the NA from the cone angle or slope of the data. $NA_x = 0.073$ and $NA_y = 0.131$ from the geometrical/theoretical M^2 (measured using Zemax) given below in Figure 3.

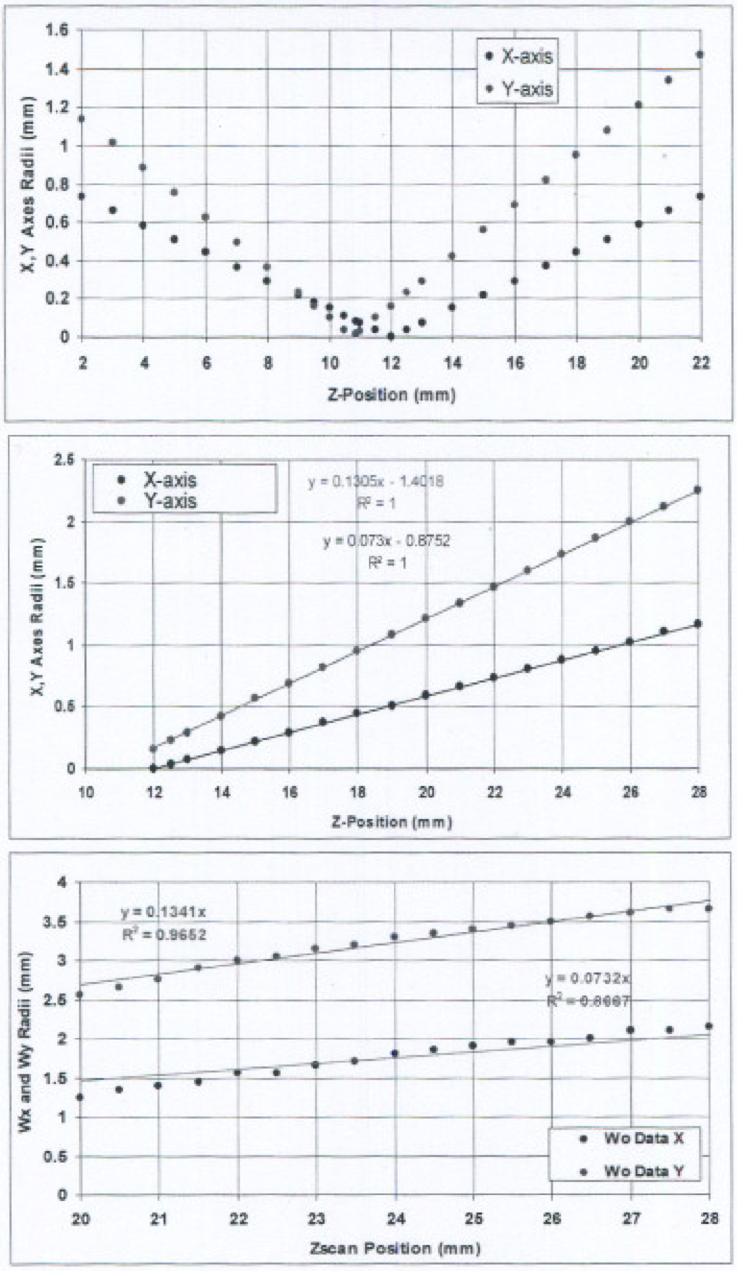

Figure 3 Shown here is the geometrical Zemax theoretical M^2 *(top chart)*, a zoomed in theoretical chart with linear fit *(middle chart)*, and the experimental *(bottom chart)*, which were used to determine the NA of each axis.

To compare these values with experimental results, an M^2 was performed on the anamorphic lens experimentally and the NA values in x and y axes were extracted from the slope. Figure 3 illustrates the comparative NA results between geometrical and theoretical M^2 data. The geometrical NA values are in good agreement with the experimental values in x and y axes. The NA was determined for each axis by finding the slope of a series of points after the focus. The experimental and theoretical (using Zemax) data match within 10% error, which most of the error is probably due to human error. The M^2 of the femtosecond beam was measured before all of the experiments performed, which enables accurate diffraction beam analysis/prediction beam propagation.

Table 2 gives both experimental and theoretical NA results of the anamorphic lens. The anamorphic lens results are compared with a commonly used spherical lens as shown in the table. The experimental and theoretical NA results show that the anamorphic lens design is functioning as predicted.

Table 2: NA values for theoretical and experimental results.

Type	NAx	NAy
Theoretical	0.073	0.131
Experimental	0.073	0.134
Instantaneous NA (at focus)	0.0035	0.256
Spherical 125mm Lens	0.022	0.022

The instantaneous NA is the NA at the desired line focus at 0µm defocus position in Figure 2, whereas, the theoretical and experimental NA results are for through focus which is similar to the average NA for each axis. Thus given here is the performance of the anamorphic lens as compared to theory and the NA for a line spread of 2.5µm x 190µm on the sample.

4. Grating Processing and Characterization

Our method of micromachining gratings uses an anamorphic lens to distribute the ultrafast (UF) laser pulse from a 5.5mm round Gaussian distribution to a 2.5µm by 190µm line shape. Each individual grating line consists of three separate line pulses in sequence (a line in x-direction). Then the xyz stage moves in y-direction by a grating spacing, d; in this case d = 20µm. The grating consists of three lines in the horizontal and 25 lines in the vertical, which equates to ~500µm x 500µm grating. Figure 4 shows a 500µm x 500µm grating in semi-insulating SiC. A grating spacing of 20µm is illustrated here, but the optimal spacing was determined by plotting the diffraction efficiency (DE) as a function of spacing in Figure 7 below.

The anamorphic line distribution processed gratings into the SiC semi-insulating sample, which were analyzed using optical microscopy and Atomic Force Microscopy (AFM) to understand the morphology of the index modified structures. The grating lines are on or just below the surface (~5µm to10µm), and the modifications form a hill on surface, which will be analyzed further with AFM. The figure below show a 10X and 50X images illustrating a good overlap of the grating lines.

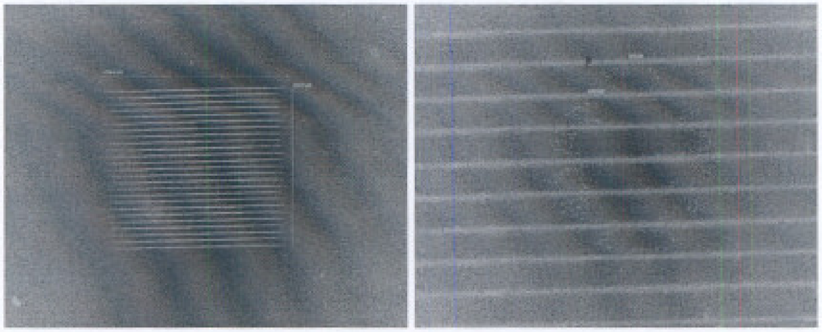

Figure 4 SiC grating view with an optical microscope using Nomarski DIC for (left) semi-insulating SiC on a 10X magnification; (right) 50X magnification. Image processing was performed in order to better resolve the modified surface lines.

For these images, the optical microscope used is an Olympus upright digital BX51 microscope with Nomarski DIC capabilities that use high contrast prisms to produce increased contrast/resolution. This microscope also has measuring capabilities to ± 0.25µm or less, which is also traceable to NIST.

Here, the 2.5µm x 190µm *predicted* line spread is actually ~4.5-5.0µm wide x 210µm long for the semi-insulating SiC sample. The processed grating was analyzed using the Nomarski DIC mode on the optical microscope (set in reflection mode). AFM was also exercised to provide more precise imaging/measurement of the line spread morphology.

Atomic Force Microscopy (AFM) was used in tapping mode to evaluate the topography of line distributions fabricated below the threshold. In addition to height images obtained from monitoring the cantilever oscillation amplitude during scanning, surface potential measurements can be obtained from monitoring the AFM cantilever response during an application of voltage, which gives us information on the electric field distribution. Figure 5 below shows some AFM results of a SiC semi-insulating sample with surface line modifications.

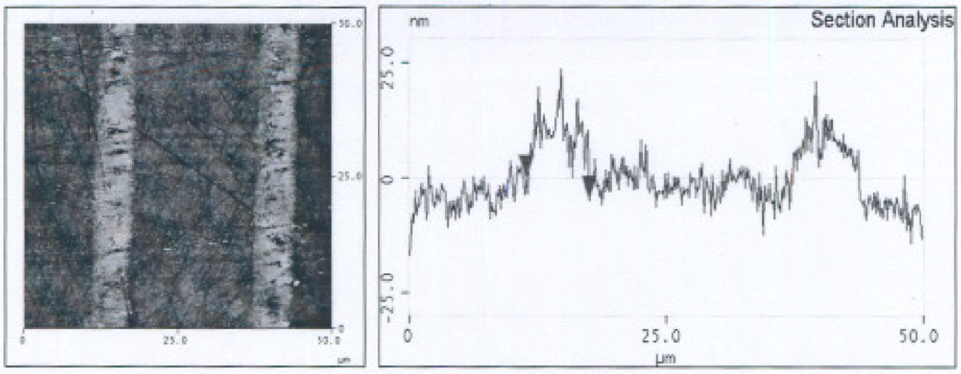

Figure 5 On the top shows AFM results of a 5.0µm wide and a 10nm raise surface modification on semi-insulating SiC material.

The AFM SiC sample results show a morphology of the line processed structures that are protruding bulges that are raised by ~10nm and have a width of ~5.0µm. The AFM concludes that the semi-insulating SiC surface modification by these line spreads creates a hill in the substrate surface, which may be due to a local subsurface restructuring has occurred or some other electronic trapping process[1] has forced the material to rise in the processed areas. The protruding lines, in addition, also caused a broader line width instead of the predicted 2.5-3.5µm due to the material forcing upward which causes non-irradiated areas to rise as well. Deeper subsurface processing causes a smaller or no protruding hill and the optical imagery illustrates a line width equal to the predicted values.

The optimal DE was determined by manufacturing a series of gratings with varying spacing, d, ranging from 3µm to 50µm. A typical DE measurement output is shown in Figure 6. This DE output shows the 0-order and diffracted beams resulting from a HeNe laser at 632.8nm, 1.5mm 1/e2 beam diameter, and 1.5mW output power. A long focal length lens was used to keep the depth of focus (or Rayleigh range) large and the spot size close to 500µm, which is roughly the size of the grating structures. The HeNe beam power and diameter were measured with Spiricon software and a Cohu CCD camera with and without the sample (in the absence of the gratings). The HeNe illuminated a specific grating in the sample, and then the zero-order (left picture in Figure 6) and 1st order (right picture in Figure 6) output beams were measure with Spiricon/Cohu. The +1 and -1 orders were verified that they contained the same power within ±5%. However, for the DE calculation only one of the orders were measured (the +1 order) and a factor of 2 exist in the DE calculation in Equation 5 below.

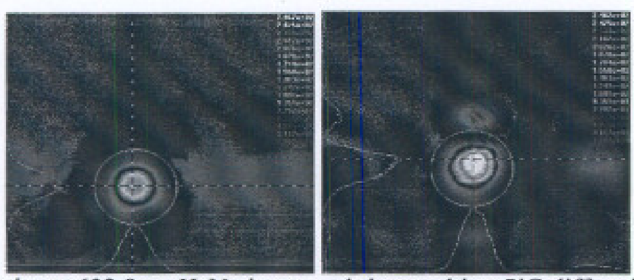

Figure 6 This figure depicts the input 632.8nm HeNe beam and the resulting SiC diffraction pattern of the first order. On the right is the 0-order beam and on the left is the first-order diffracted beam.

The DE of the 1st order diffraction pattern in Figure 6 was calculated by first measuring the power of the 1st order then using the following equation,

$$DE = \frac{2 \cdot P_1 \cdot 10^{-(ND_0 - ND_1)}}{P_o} \cdot 100. \qquad \text{Equation 2}$$

In Equation 5, P_1 is the 1st order measured power, P_o is the zero-order power, ND_0 is the density filter OD placed in front of the Cohu camera when measuring the zero-order beam (no grating present only the unprocessed sample), and ND_1 is the neutral density filter OD placed in front of the Cohu camera while measuring the 1st order diffraction pattern. Equation 5 was used to calculate the DE for each grating fabricated. Figure 7 gives the results of the DE calculated for each grating produced.

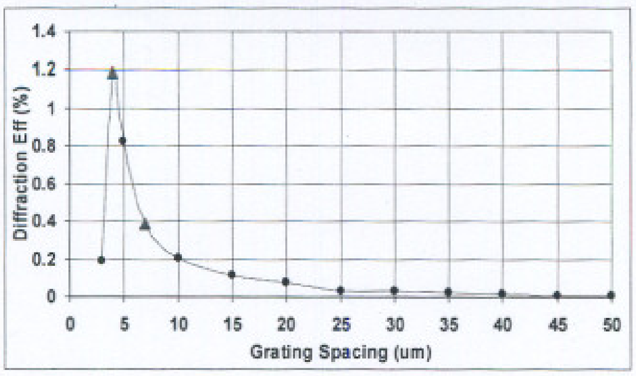

Figure 7 DE verses grating spacing.

Figure 7 demonstrates how the DE peaks at a grating spacing of 4µm. These DE results are primarily shown here to illustrate how the gratings generated, using this anamorphic lens technique, in SiC present a practical alternative method of constructing gratings in transparent materials. One functional application for this technique is manufacturing fiber Bragg gratings (FBG) [6]. This technique can generate gratings without removing the cladding, using a phase mask, or adding dopant to the fiber to react to the UV interfering beams to create the FBG.

5. Conclusion

In this work we report a new way of processing transparent bulk materials using an anamorphic lens design that enables a single femtosecond pulse to modify the surface and/or subsurface with a change in the bulk index of refraction. The theoretical anamorphic lens design agrees well with the experimental characterization M^2 and NA results. The gratings manufactured are ~500µm x 500µm and consist of ease and good alignment of the individual line pulses. Optical microscopy and AFM results show the morphology of these grating lines to be in good agreement with the predicted results, but without the broadening of the line width caused by the protruding hill. Depending on the subsurface depth and type of substrate irradiated, a protruding will form above the surface. The DE results illustrate the performance of the gratings fabricated in SiC. The reported DT measurements are directly proportional to the referenced bandgap energies.